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Courtyard housing in midrise buildings: An environmental assessment in hot-arid climate

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ABSTRACT

This study is an evaluation of the environmental impacts of courtyard integration in midrise housing in the hot-arid climate of Dubai, The United Arab Emirates. Computer simulation is utilized to determine the overall energy consumption, energy savings potential and available daylight levels. The study is carried out in three steps. First, a comparison between conventional and courtyard buildings is conducted. Second, the effects of number of floors, type of glazing, wall thickness and insulation type & thickness on the performance of a courtyard type building are simulated. Lastly, an optimized courtyard model encompassing the best of each of the parameters studied in the second step is generated and tested. Converting a six-floor building from the conventional form to a courtyard form, keeping all building materials and parameters the same, resulted in a 6.9% reduction in the year-round total energy consumption. The optimized courtyard model, including variations on building materials, resulted in 11.16% reduction in the overall year-round energy consumption when compared to the reference conventional form building. Comparison between the daylight performance of the two forms showed that the courtyard form was better than the conventional form during both winter and summer test days with daylight factor values close to those recommended by the USGBC, which means that the courtyard form provides more usable daylight without excessive glare.

1. Introduction

The building industry in developing countries constitutes a very important contributor to the overall ecological footprint. The residential buildings account to massive 40% of the total carbon dioxide emissions, 40% of all energy usage, 68% of electricity utilization, 10% clean water consumption and 50% of non-industrial waste generation [1]. The United Arab Emirates is one of the fastest growing urban countries in the Middle East and this brings both opportunities and responsibilities. This growth has been extremely fast lately causing environmental issues, such as increased pollution, increased energy consumption, depletion of natural resources, poor air quality and increased human health concerns. The ecological footprint (EF) per person in the UAE is estimated at 11.9 global hectares, which is six times higher than the world average bio-capacity per person, and 14 times higher than the carrying capacity per person which is only 0.8 global hectares [2]. Selections made in the housing sectors, such as typologies and materials, contribute radically to the energy consumption. For example, the contemporary models of housing with large glass facades are more desired choice today in the building construction in the UAE, and yet considerably contribute to the heat built-up inside buildings which leads to increased air conditioning requirements as well as amplifying the heat island effect.

The courtyard form is one of the oldest building forms used by humans. They are found in all times, climates and locations, e.g. Iran, China and Middle East [3]. Furthermore, this typology represents a good response to the climate, culture and society in the Middle East region. The use of inappropriate housing forms of other regions, such as the freestanding form in the center of the plot does not perform well in the harsh climates of the Middle East region. In the UAE, housing typologies have been imported from western countries rather than adopting and employing traditional concepts into contemporary forms, making the freestanding form the dominant housing form. Different parameters define the courtyard geometry and thus its response to the climate such as length, width, height and aspect ratio [4,5]. Hakmi [3] developed the concept of the courtyard into the modern housing fabric both in single and multi family dwellings. He proposed alternative types for midrise dwellings which differ in their dimensions, heights and types.

On the climatic performance of the courtyard form, many research works have been done in low-rise buildings across different climates to address the thermal, shading, daylight and airflow characteristics [6–15]. Aldawoud and Clark [6,7] stated that

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courtyard integration is found to be energy efficient in all climates, specifically in the hot arid and hot humid climates. The authors also concluded that the low U-value glazing with lower percentage of wall coverage results in reduced energy consumption. Moreover, they suggested integrating the courtyard into low and midrise building, whereas the atrium was found to be more energy efficient in high-rise buildings. Muhaisen and Gadi [8–11] concluded that deep and elongated courtyard forms achieve maximum internal shading area in summers, which results in less energy consumptions. On the other hand, shallower courtyard forms allow high solar gain and results in less heating loads in winters. Meir et al. [12] concluded that the geometry and orientation of the courtyard influence its thermal behavior. Additionally, it was found that adequate airflow movement enhances the thermal performance during summer daytime. Al-Hemiddi and Al-Saud [13] proved that the courtyard integration along with the cross ventilation effect results in significant enhancement of cooling the interiors and thus great impact on the energy reduction. Rajapaksha et al. [14] argued that the comfort zone of a courtyard house in warm humid climate can be extended to higher humidity and temperature by utilizing higher air velocities, along with the evaporative cooling effect of water surfaces. Sharples and Bensalem [15] stated that the best ventilation performance of a courtyard is on the roofs positioned to face negative pressures perpendicular to the building, while the roof positioned to face positive pressures needs a large openings area to enhance the ventilation effect.

The previously cited works indicate that most of the studies were concerned with the courtyard housing in low-rise buildings. Nevertheless, proposed models of midrise courtyard housing lacked an assessment methodology to proof their energy efficiency in the given climates. The purpose of this research is to assess, through computer simulation, the energy performance of midrise housing with an integrated courtyard in hot arid climate and to evaluate its behavior against different parameters, such as thermal, solar shading and daylight. Moreover, different variables are chosen then tested to draw the optimal design parameters of the courtyard form such as height, glazing type, wall thickness, insulation material and insulation thickness.

2. Research outline

This research is conducted in three steps: firstly, selected variables will be fixed then assessed in both forms: the conventional and the courtyard midrise housing, both sharing equal built-up area. This allows direct comparison between the two forms while subject to the same limitations and functionality. Secondly, the courtyard midrise form will be tested against the different proposed study parameters, to quantify the achievable energy savings over the range of values for each parameter. Lastly, a six-level courtyard model with these optimal variables will be simulated and then compared to the conventional model to represent the optimum performance in terms of the energy reduction.

2.1. Step 1: Assessment of conventional versus courtyard form

The annual energy consumption, along with other data, will be compared in both forms: without and with the courtyard incorporation. The two forms constitute six levels of typical floors and both are formed from units of equal built-up. On the other hand, all floors have the same courtyard to built-up area ratio in each flat, which is equal to 50/175, except the first level where this ratio is equal to 25/200. The selection of six-floor height is based on the common practice in Dubai for the midrise housing buildings, which range from four to six floors. Moreover, four units (same type) are utilized to form an inner void in which the apartments' courtyards are all located around the inner void center to create an introverted courtyard-housing block. As for the conventional from, the same steps are followed, except that the four units are rotated around their solid ends and the apartments' courtyards are all located around the outer boundary to create an extroverted conventional housing block (Fig. 1).

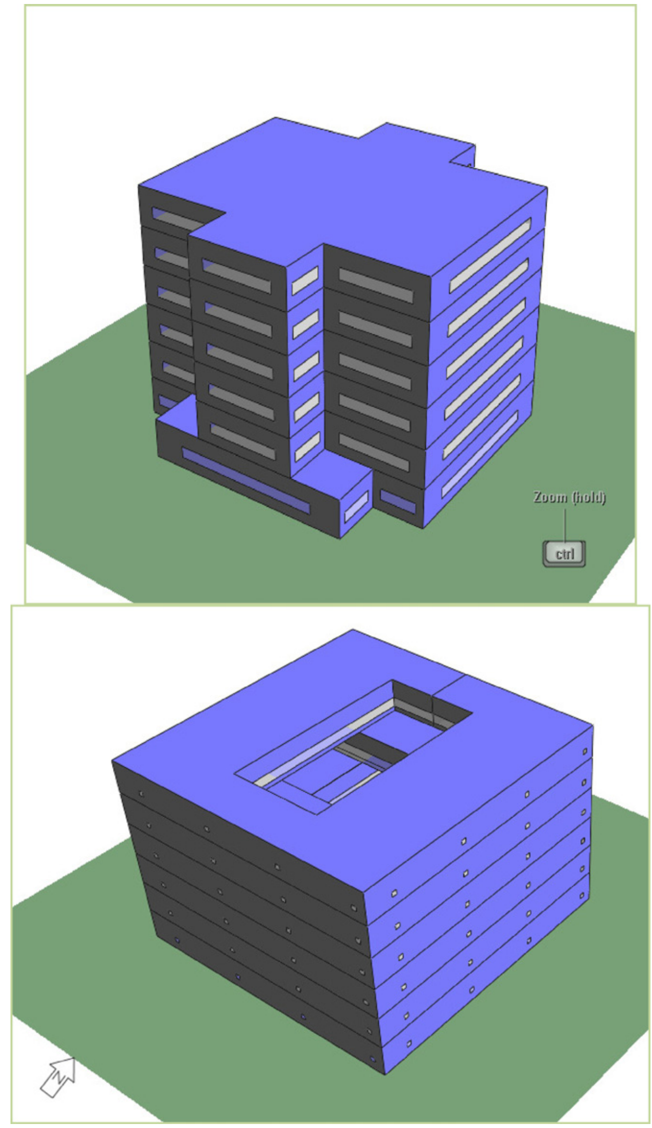

Fig. 1. Comparison between six-floors of conventional (top) and courtyard forms (bottom).

2.2. Step 2: Assessment of different variables within the courtyard form

Initially, the model is assessed in different heights within the midrise context: 4, 6, 8 and 10 floors, while other variables remain constant. Secondly, three glazing types are tested: single glazing, double glazing (Low-e) and triple glazing (Low-e). Thirdly, the model is tested in different wall thicknesses: 15, 20, 25, 30 and 40 cm. Fourthly, five insulation materials are tested: Dense EPS Insulation, Glass-Fiber Quilt, Phenolic Foam, ASHRAE Air Cavity [17] and Cellular Polyurethane. Fifthly, different thicknesses for the reference insulation material are tested: 2.5, 5.0, 7.5 and 10 cm. Finally, the optimal value for each variable is decided based on the maximum reduction of the annual energy consumption (Table 1).

Table 1
Matrixes of variables of the courtyard model. The reference value for each variable is highlighted.

Parameter (variable)	Number of storey	Glazing type	Wall thickness (cm)	Insulation material	Insulation thickness (cm)
Courtyard model	4	Single glazed	15	Glass-Fiber Quilt	2.5
	5*	Double glazed (Low-e)	20	EPS (Styrofoam)	5.0
	6	Triple glazed (Low-e)	25	Phenolic foam	7.5
	7*		30	ASHRAE Air Cavity [17]	10
	8		40	Cellular polyurethane	
	10				

* Additional floors added later in the study.

Table 2
Area details of the study models as per IES calculations.

	Volume (m^3)	Floor area (m^2)	External wall area (m^2)	External opening area (m^2)
Courtyard	15 050	4300	3710	504
Conventional	15 050	4300	2520	504

2.3. Step 3: Assessment of optimum courtyard form versus conventional form

The courtyard form, with variables set to optimal based on the second step outcomes, will be compared to the conventional form. The height will be fixed to six-floors as per the first step settings. The result will draw the best parameters that can be incorporated in the courtyard form to achieve highest energy saving in the given climate.

3. Methodology

Several methods have been used in the past in the study of similar research. This included wind tunnel modeling [18], experimental field measurements [19] and survey [20]. But the most commonly used technique is computer simulation [9,14,20–22] including Computational Fluid Dynamics (CFD) [23–25]. Computer simulation offers a powerful yet convenient method to test a wide range of parameters and configurations in a relatively short period of time and at a lower cost. Thus computer simulation method was selected in this study.

A wide range of commercial simulation software is available and has been use in the past. The computer simulation tool Virtual Environment by Integrated Environmental Solutions (IES-VE) has been used extensively in the past due to a combination of accuracy and being user-friendly [26]. IES-VE is an integrated building's performance analysis platform. IES provides a range of different analysis options and capabilities, which give detailed simulations of the building, such as building loads, carbon emissions, daylight, solar analysis and airflow. The IES software is a package of various modules in which each deals with a certain calculation. Many published works have successfully used IES-VE as the simulation tool [9,14,26]. Thus, the IES-VR software was chosen to carry out this research due to its accuracy and capabilities. The IES-VR software has been in commercial use for over 20 years and has undergone multiple internal and external validation tests [17].

Table 2 summarizes the geometrical data related to the total volume, floor area, external wall area and external opening area, for both the conventional and courtyard models used in the first step. Although the conventional and courtyard forms have equal volume and total floor area, the external walls area in the courtyard form is 47.2% larger than in the conventional form. On the other hand, the external opening area is equal in both forms, though it constitutes different percentages with respect to the external walls area, which is 14% in the courtyard form and 20% in the conventional form.

As for the opening configurations, the courtyard model is mostly opened facing inside, while the outside walls have minimal openings in terms of area and size to maintain privacy and avoid high solar glare.

4. Results and discussion

4.1. Step 1: Assessment of conventional versus courtyard form

4.1.1. Thermal simulation

The simulation results show a 54.25% reduction in solar gain for the courtyard form compared to the conventional form. This is expected as most openings in the courtyard form are shaded and located into the controlled microclimate of the courtyard space, compared to the conventional one. As for the external conduction gain, the courtyard form shows 54.15% increase compared to the conventional form due to the larger area of external surfaces in the courtyard form. As shown earlier, Table 2 shows 47.2% higher external walls in the courtyard form than the conventional. Therefore, the heat transfer is higher due to the large external exposure in the courtyard model. However, it is noticed also that the conduction gain percentage is higher than the external wall percentage. This is due to the extra conduction heat transfer from the extra inward facing external surfaces formed by the rotated floors in the courtyard form (Fig. 1). Fig. 2 shows the values of the conduction heat transfer, solar gain and the total energy consumption for both the conventional and courtyard forms. The results show a net reduction of 6.9% in the total energy consumption of the courtyard form compared to the conventional form. Note that the total energy consumption is limited to the cooling loads and it excludes heating

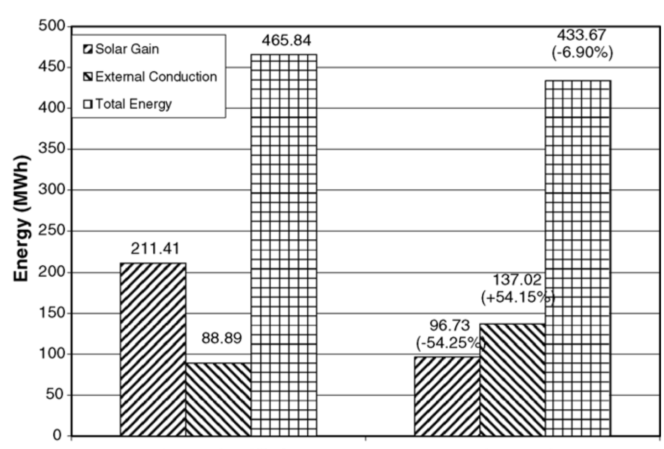

Fig. 2. Energy breakdown for the conventional and courtyard forms.

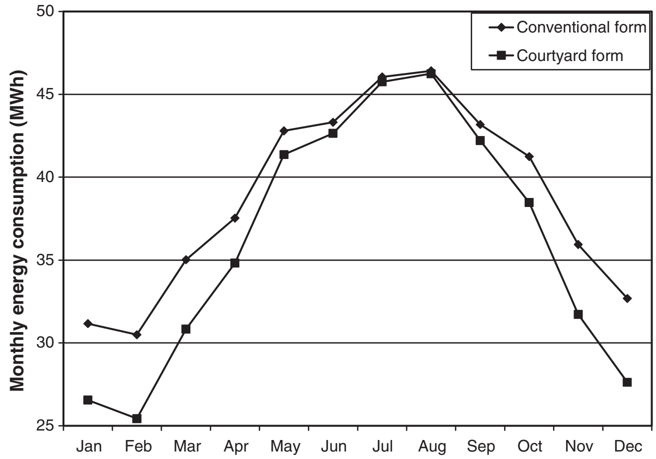

Fig. 3. Monthly energy consumption of conventional and courtyard models.

systems, lighting and appliances all of which we assumed constant in all cases.

Fig. 3 shows the monthly energy consumption of the conventional and courtyard models. The energy performance of the models conforms largely in the hottest months of June, July and August, while the rest of year shows a significant distinction on the energy performance, which influences the overall energy scenario. This behavior in the hot months can be explained based on Muhaisen's conclusion [8] that despite the shading effect on the reduction of cooling needs in summer generally, high sun altitude results in considerably less shaded area, whereas places with lower sun altitude become more responsive by increased shaded areas during summer. Additionally, the higher conduction gain of the courtyard model in summer affects its energy performance, as more cooling loads will be needed.

4.1.2. Daylight analysis

The illuminance and daylight factors are calculated in the conventional and courtyard models by FlucsDL, IES Software. The results represent the values of daylight as numerical and graphic outputs. Two daylight scenarios are selected based on the Solar Shading Calculations. The two days represent low and high solar radiations received by models surfaces on solstice days: December 21st at 4:00 PM (solar shading 16.67%) and June 21st at 12:00 PM (the highest solar shading 85.27%). The selected dates represent the two extremes throughout the whole year. Fig. 4 shows daylight factors (DF) for both forms on December 21 at 4:00 PM. The conventional form had an average DF of 14.5% while the courtyard form has an average DF of 6.3% on the same date and time. Fig. 5 shows daylight factors (DF) for both forms on June 21 at 12:00 PM. The conventional form had an average DF of 10.1% while the courtyard form has an average DF of 5.6% on the same date and time.

The above results show that the courtyard model performs better in terms of daylight factor on both winter and summer days than the conventional form. Also the average daylight factors of 6.3% and 5.6%, for the winter and summer days, respectively, are close to the USGBC recommended daylight factor level of 5% [16]. This means that the courtyard form requires less usage of passive strategies to control daylight and glare than the conventional form.

4.2. Step 2: Assessment of different variables within the courtyard form

4.2.1. Height

Buildings with different heights have different floor areas. Thus it is not practical to use the absolute values of total energy consumption for comparison. In this case the normalized total energy consumption is used (kWh/m^2), where the total energy consumption is divided by the total floor area. Fig. 6 shows the changes in the normalized total energy consumption as a function of building height. In general, the taller the building the lower is the specific total energy consumption. This could be explained by the fact that as the number of floors increases the area of the roof remains the same. The exposed roof has the highest levels of solar gain and conduction heat transfer due to its large exposed surfaces. Reducing roof's relative exposed area in comparison to the building's overall exposed area would result in a reduction on the normalized total energy consumption of the building. This is particularly significant at low heights where the roof's relative area is significant, e.g.

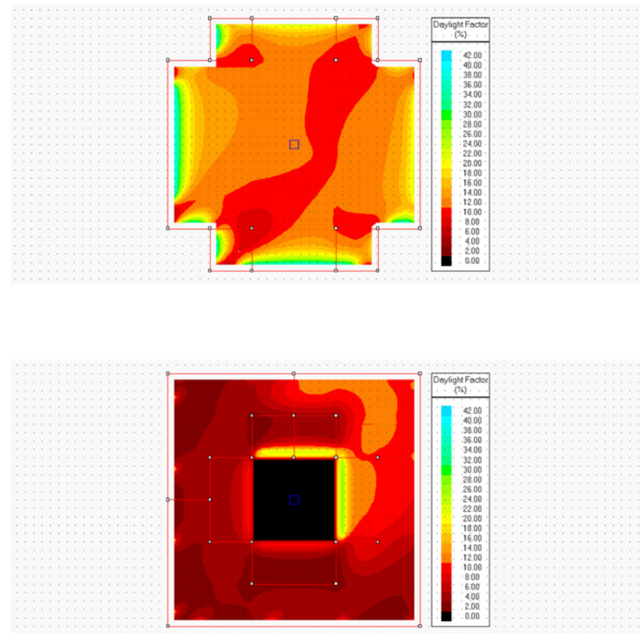

Fig. 4. Daylight factor (%) in conventional form (top) and in the courtyard form (bottom), December 21, 4:00 PM (IES).

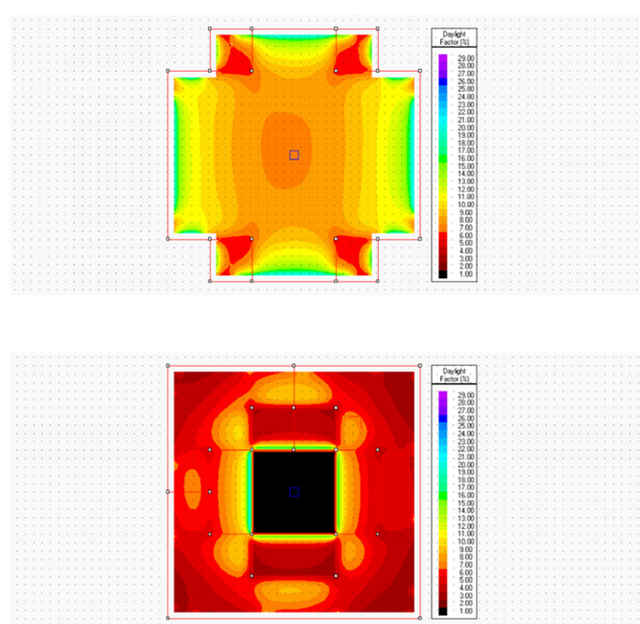

Fig. 5. Daylight factor (%) in conventional form (top) and in the courtyard form (bottom), June 21, 12:00 PM (IES).

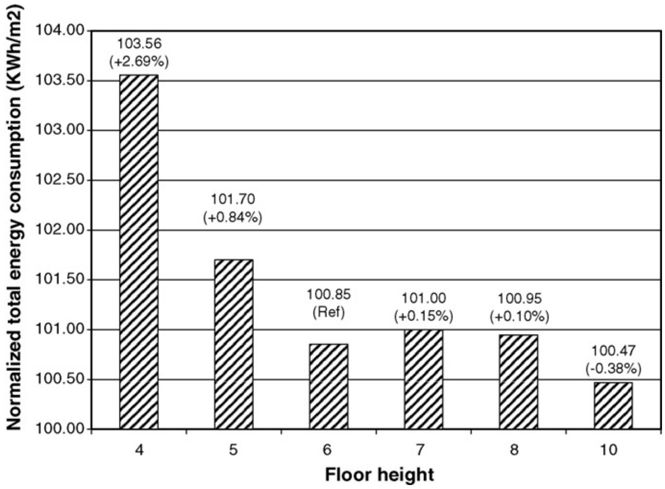

Fig. 6. Normalized total energy consumption of the selected heights of the courtyard model.

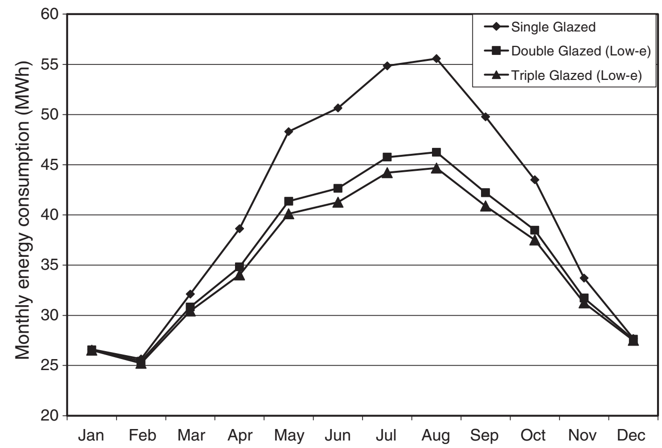

Fig. 8. Monthly energy consumption of the different glazing types in the courtyard model.

the 0.59% reduction achieved when the building' height was raised from 6 to 8 floors as seen in Fig. 6. Shallower courtyard buildings also allow more solar heat gain into the center of the building [8]. This effect becomes less significant for high buildings as the roof's relative area is already small and thus further reductions by means of increase height would not have a significant effect, e.g. the 0.34% reduction achieved when the building' height was raised from 8 to 10 floors as seen in Fig. 6.

4.2.2. Glazing type

Fig. 7 shows the simulation results of three different glazing types in the courtyard model. The single glazing type has the highest energy consumption as it is 12.31% higher than the reference model, while the triple glazing type shows a mere improvement of 2.32% on energy reduction. The difference in the reduction rates going from single to double glazing versus going from double to triple glazing is due to the different rates of heat conduction through the different layers, which depend significantly on the temperature differential between the two sides of each layer. It is identified that temperature difference between outside and inside is high compared to the difference between the two intermediate spaces. Consequently, the energy consumption drops dramatically in the double-glazed compared to the single glazed model, whereas the drop is smaller between the double and triple glazed models. This reduction can be evaluated against the cost when shifting from the double to triple glazing type, as the added cost might not have equal effectiveness or return on the energy reduction. On the other hand, the monthly energy consumptions of the selected glazing types vary largely mostly during March through November, whereas the variation diminishes dramatically during January, February and December. This is primarily due to the high temperature difference between inside and outside during hot seasons (Fig. 8).

4.2.3. Wall thickness

Fig. 9 shows the effect of the wall thickness on the energy consumption in the courtyard form, recall that the reference wall thickness is 25 cm (Table 1). The insulation thickness remained constant at 5 cm for all wall thicknesses shown in Fig. 9. Reducing the wall thickness to 15 cm resulted in a 0.6% increase in the total energy consumption while increasing the wall thickness to 40 cm resulted in a 0.9% reduction in the total energy consumption. This indicates that wall thickness have a small impact on the year-round total energy consumption. This suggests that designers are better off focusing on alternative strategies, some of which are included in this research, to achieve more significant reductions in the total energy consumption. In other words, the initial investment of implementing higher wall thicknesses is most probably much more than the savings in running costs due to the reduction in the overall energy use.

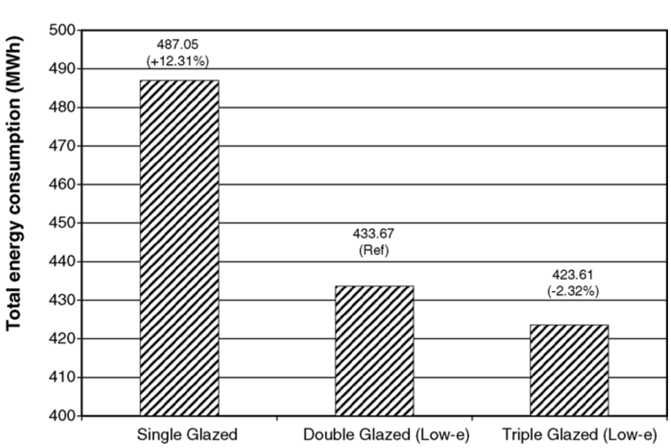

Fig. 7. Total energy consumption of the different glazing types in the courtyard model.

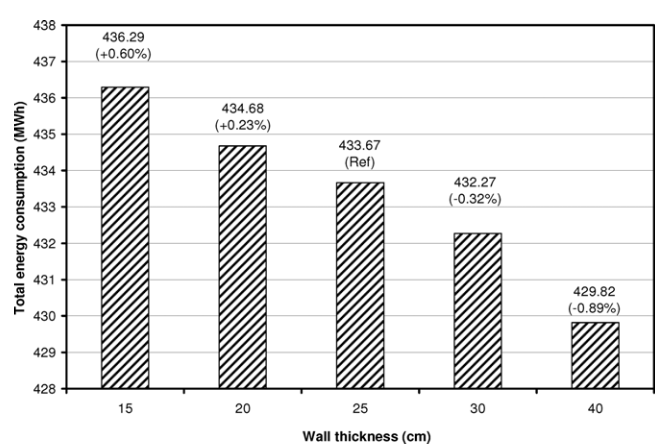

Fig. 9. Total energy consumption in the selected wall thicknesses in courtyard model.

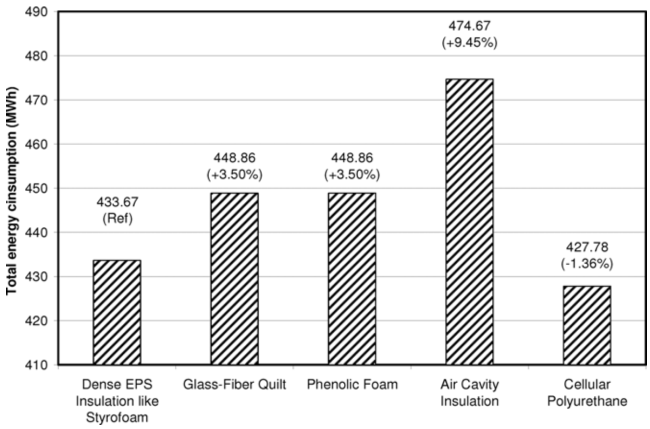

Fig. 10. Total energy consumption of the selected insulation materials of courtyard model.

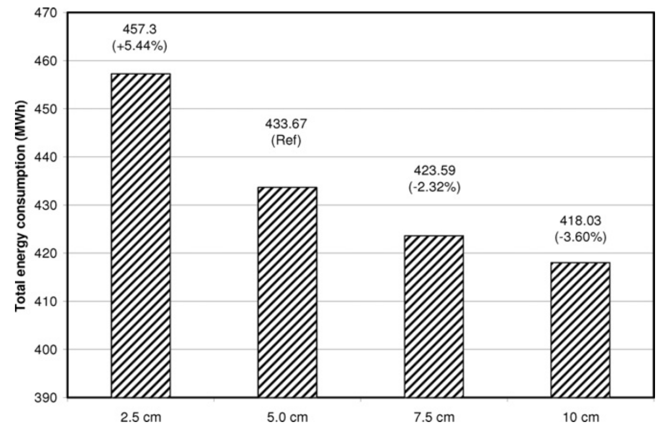

Fig. 12. Total energy consumption of the selected insulation thicknesses of courtyard model.

4.2.4. Insulation material

Fig. 10 shows the total energy consumption values with regard to the selected insulation materials. It shows that Cellular Polyurethane has the highest value of energy saving (−1.36%), whereas the ASHRAE type Air Cavity Insulation [17] shows a large increase in energy use (+9.45%) compared to the reference model. The Glass-Fiber Quilt and Phenolic Foam share the same conductivity value but differ in density and heat capacity yet both materials result in exactly the same total energy consumption. The simulation results prove that the total energy consumption is primarily a function of the conductivity value of the insulation material. The impact of other properties (density and heat capacity) might be limited to the time lag of their thermal response. It is also noted that the insulation materials in the courtyard model vary largely in energy saving mostly during March through November, whereas the variation reduces in January, February and December. This is primarily due to the high temperature differential between inside and outside during hot seasons (Fig. 11).

4.2.5. Insulation thickness

Fig. 12 shows the energy consumption values with regard to the selected insulation thicknesses. The 10-cm-thick insulation has the highest return on energy saving (3.60%) with reference to the base model, whereas the 2.5-cm-thick wall increases the energy use by 5.44% with reference to the base model. Moreover, the increase of energy use in the 2.5 cm wall thickness is noticeably higher than the rest of the variables set, whereas thicknesses of 5, 7.5 and 10 cm relatively reduce the energy use by slightly more consistent differences. The effect of the insulation material thickness was mainly during the hot months. It is at those months that the temperature differential between the inside and outside is highest and the presence of the insulation material is most needed (Fig. 13).

4.3. Step 3: Assessment of optimum courtyard form versus conventional form

Based on the previous simulation results, an optimized 6-floors courtyard model (referred to as courtyard B) is tested against the 6-floors conventional model (reference model in this study) in terms of energy saving. The optimal parameters used in the courtyard B model are: Triple Low-e Glazed openings, 40 cm wall thickness and Cellular Polyurethane with 10 cm thickness. Fig. 14 shows the energy consumption of the reference conventional form and the two courtyard models (A and B). Courtyard form (B) has a higher energy saving compared to the previously proposed courtyard form (A) with an energy savings of 11.16% compared to 6.90% in the courtyard form (A).

Fig. 15 indicates the monthly energy performance of the conventional as well as the two courtyard forms. Looking at the monthly values, it is observed that the two courtyard models act similarly from November to March, whereas the optimum courtyard model (B) performs significantly better in the hot months for the rest of the year. This means that courtyard model (B) is more effective than the conventional form year round, unlike the courtyard

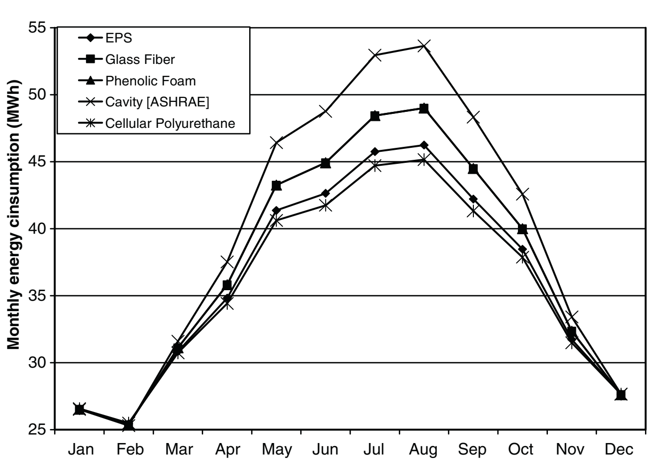

Fig. 11. Monthly energy consumption of the selected insulation materials in the courtyard model.

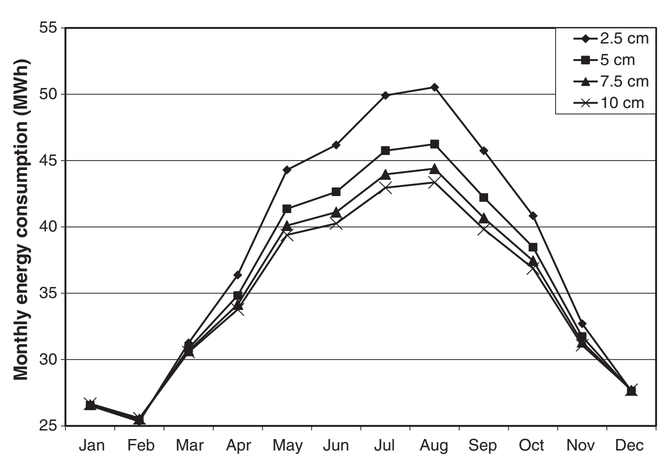

Fig. 13. Monthly energy consumption of the selected insulation thicknesses in the courtyard model.

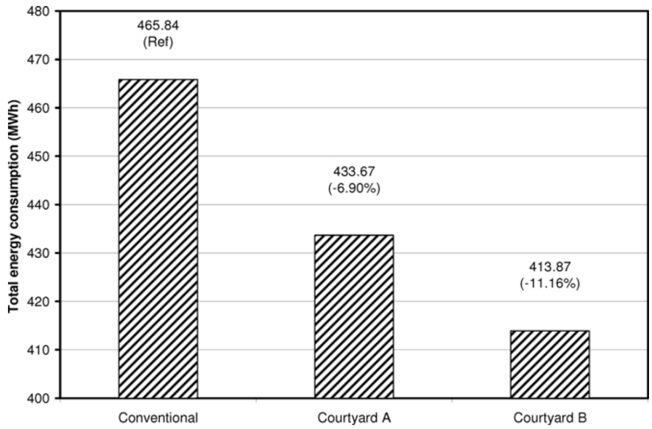

Fig. 14. Total energy consumption of the conventional, courtyard A and courtyard B.

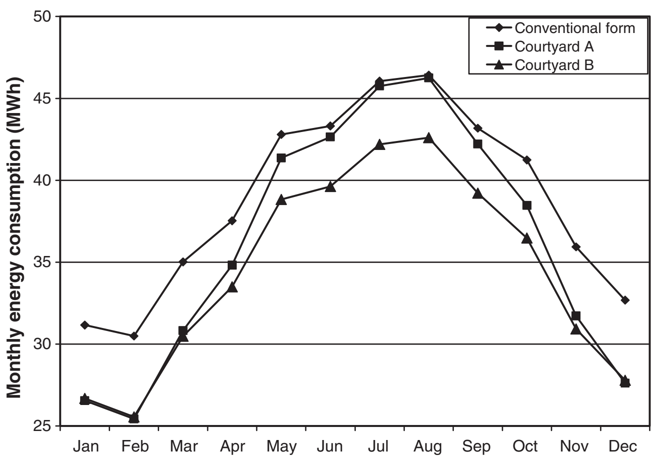

Fig. 15. Monthly energy consumptions of the conventional, courtyard A and courtyard B.

model (A) which drops in cooling efficiency during hot months of the year. Based on that, the weak energy performance of courtyard model (A) during summer can be overcome by altering the model towards optimal values of variables such as thicker walls, improved insulation and glazing.

5. Conclusions

In this research, the impact of integrating a courtyard in the design of midrise buildings on the year-round energy consumption was simulated subject to the hot and humid weather conditions of Dubai, UAE. The simulation was performed using the IES-VR commercial package. Using similar building materials, a courtyard form building used 6.9% less year-round total energy than a six-floor conventional form building with similar built up area. Additionally, the courtyard model performed better in terms of daylight factor on both winter and summer days than the conventional form. Then some parameters within the courtyard form were varied and their effect of the year around total energy consumption was gauged against that of the reference courtyard model. The parameters tested included: number of floors, type of glazing, wall thickness, and insulation type and thickness. With the exception of the effect of number of floors, all cases simulated were compared to a reference conventional form building that utilizes current design and built practices in Dubai, UAE. The change in the year-round total energy consumption ranged from +12.31% (case with single pan glazing) to −3.60% (case with 10 cm insulation thickness). Some parameters showed minimal effect on the energy consumption, i.e. wall thickness and insulation density & specific heat capacity. Once the best value for each parameter was determined independently, an optimized courtyard form building incorporating best value for each parameter was modeled and tested. This optimized model achieved a total energy reduction of 11.16%. This research shows that courtyard form in midrise buildings has the potential to save significant amounts of energy when used in climates similar to Dubai, UAE.

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